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Cloudy and clear stratospheres before A.D. 1000 inferred from written sources

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[1] How can observational information about stratospheric transparency in the preinstrumental era be acquired today? It may be reasonably assumed that a high turbidity in the stratosphere is almost always caused by light-scattering sulfate aerosols derived from large volcanic eruptions. Historical reports of a dimming of the Sun, red twilight glows, reddish solar haloes, and dark total eclipses of the Moon indicate a high turbidity; contrariwise, a ruddy disk shown by the eclipsed Moon betrays a clear stratosphere. On the basis of an extensive search of primary European and Middle Eastern written sources pertaining to the ancient and early medieval periods, seven stratospheric dry fogs, in addition to the four major ones already known, have been identified by using solar observations, and five smaller ones have been detected from dark total lunar eclipses. Seven of the eight most important dry fogs between 300 B.C. and A.D. 1000 can be either definitely or plausibly correlated with high levels of sulfate acidity observed in Greenland ice cores. An important conclusion is that this sample is probably very nearly complete for major dry fogs during this period. A second conclusion is that the ratio of dark to normal total lunar eclipses during early medieval times (A.D. 400–1000) appears to be equal, approximately, to the ratio that has prevailed for the past 40 years. These conclusions suggest that the frequency of volcanic eruptions, both large and moderate, throughout the world may have remained statistically constant (on a long timescale) since at least 300 B.C. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0370 Atmospheric Composition and Structure: Volcanic effects (8409); 1704 History of Geophysics: Atmospheric sciences; 1749 History of Geophysics: Volcanology, geochemistry, and petrology; *KEYWORDS:* aerosol, historical sources, ice cores, lunar eclipses, solar observations, stratosphere

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1. Introduction

[2] The stratosphere was recognized and named in 1900 in the course of a series of in situ balloon measurements [*Goody*, 1954]. Some of its properties, however, had already been discovered visually from the ground by investigation of the atmospheric aftereffects of the great eruption of Krakatau Volcano in 1883 [*Symons*, 1888]. Since modern studies of volcanic eruptions since 1900 have confirmed the validity of these remote ground-based observations [*Stothers*, 1996], similar reports made in even earlier times can now be safely used to infer past periods of notable volcanic disturbances to the stratosphere.

[3] What, specifically, are the visible atmospheric effects that explosive volcanic eruptions produce? Most readily noticed are (1) a reddening and a dimming of the Sun and other stars; (2) red or purple twilight glows; (3) reddish haloes (Bishop's rings) around the Sun; and (4) dark total eclipses of the Moon. These phenomena are all caused by the scattering of incident sunlight (or starlight) by sulfuric acid aerosols in the stratosphere. Volcanoes inject into the stratosphere the primary gas SO_2, which combines with H_2O in a series of heterogeneous reactions to form H_2SO_4 aerosols. Stratospheric winds then distribute the aerosols around the hemisphere or, in the case of tropical eruptions, around the globe. The aerosols may reside in the stratosphere for up to 2–4 years depending on the altitude of injection. In the case of effusive or fissure-type eruptions, most of the SO_2 may never reach the stratosphere. In that case, the lifetime of sulfuric acid aerosols in the tropospheric layers of the atmosphere would not exceed a few days. On the other hand, large fissure eruptions often last for months, and therefore the local troposphere may remain polluted with aerosols for up to half a year and sometimes longer. For such eruptions, the chief atmospheric effects are a reddening and a dimming of the Sun and other stars. In all cases, the stratospheric and tropospheric aerosols are said to constitute a dry fog.

[4] A few noteworthy dry fogs from early volcanic eruptions have recently become the subject of detailed investigation. These include dry fogs due to Tambora (1815), Laki (1783), Eldgjá (934), and unidentified volcanoes in A.D. 1258, 626, and 536, and in 44 B.C. (see the review by *Stothers* [1999], and references therein). To

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extend the existing investigation to lesser dry fogs that occurred before A.D. 1000, a more intensive study of published historical documents has been undertaken, looking now at more than just the years when an eruption was already known from independent evidence found in ice cores and tree rings. The geographic areas included are all of Europe and the Middle East, and the methods of study follow those that were used before for the eruptions of 44 B.C. and A.D. 536 and 626 [*Stothers and Rampino*, 1983a].

[5] An important additional body of literature from the Middle East has now become available in English translation, namely, cuneiform texts written between the eighth century and the first century B.C. [*Hunger and Pingree*, 1999]. These texts include astronomical and meteorological diaries that provide almost day-to-day observational data for the core period from the fourth century to 61 B.C., as recorded at Babylon.

[6] Another geographic area providing potentially useful texts is the Far East, especially China [*Yau and Stephenson*, 1988; *Pang*, 1991]. Although researchers have by no means exhaustively searched the extant Far Eastern literature, the results have been slender. Reports of observations of solar and stellar dimming have turned up only for the eruptions of 44 B.C. and A.D. 536. Furthermore, most reports of lunar eclipses in the ancient Chinese literature appear to refer to theoretically calculated eclipses [*Schove*, 1984].

[7] *Scuderi* [1990a] has attempted to use Chinese reports of prolonged sunspot visibility and of "black vapors" seen near the Sun to infer the presence of volcanic aerosol veils. He finds a statistically significant correlation of these sightings with the times of reduced northern hemisphere temperatures as deduced from narrow annual tree ring widths, such as might be expected to occur in the aftermath of a large volcanic eruption. On the other hand, his results can be only statistically valid in view of the ambiguity of the Chinese reports, whereas we are here interested in specific definite cases. Moreover, reports of sightings of this kind have not been associated with volcanic eruptions in more recent centuries.

[8] Generally speaking, our scientific information about early volcanic aerosol veils comes from Europe and the Middle East. For the centuries before A.D. 1000, the data are very spotty, being dependent on the vagaries of manuscript survivals and on what was deemed by ancient and medieval writers to be worthy of reporting. In addition, due to frequent corruptions in text transmission, later compilations must be used as sparingly and as cautiously as possible; contemporary writings are much to be preferred whenever available. Probably all dry fogs from the greatest eruptions since 600 B.C. have been mentioned in the extant literature, as has been surmised from a direct comparison of the written record [*Stothers and Rampino*, 1983b] with the glaciochemical record of sulfate acidity in the annual layers of dated polar ice cores [*Hammer et al.*, 1980]. For the smaller eruptions that are less than Tambora-class, completeness is obviously impossible despite our making a comprehensive search of the extant literature. We shall find, however, that the threshold of dry fog detection using solar observations reported in available documents is approximately the same as the threshold using polar ice cores as estimated by *Robock and Free* [1996] and *Clausen et al.* [1997]. With lunar eclipse observations we can do even better.

[9] Ancient and medieval authors and (where necessary to avoid ambiguity) the titles of their works will be cited here directly in the text. Modern compendia of some of their works are referred to by using the following abbreviations: Bollandists, Bollandist Fathers' *Acta Sanctorum*; Bouquet, Bouquet's *Recueil des Historiens des Gaules et de la France*; *CSBH*, *Corpus Scriptorum Byzantinae Historiae*, Bonn Series; *MGHAA, Monumenta Germaniae Historica Auctores Antiquissimi*; *MGHSRM, Monumenta Germaniae Historica Scriptores Rerum Merovingicarum*; *MGHSS, Monumenta Germaniae Historica Scriptores*; *PG*, Migne's *Patrologia Graeca*; *PL*, Migne's *Patrologia Latina*; *RIS*, Muratori's *Rerum Italicarum Scriptores*.

[10] In section 2 we present the evidence for dry fogs based on observations of the Sun and other stars, as well as on reports of red twilight skies and other phenomena. Section 3 contains the evidence using dark total eclipses of the Moon, along with known observations of normal lunar eclipses. A simple statistical analysis and a summary of our results conclude the paper in section 4.

2. Solar Observations

[11] Dry fogs can be difficult to differentiate from more familiar meteorological phenomena that dim the Sun and other stars unless adequate information is available concerning the duration of the observing haze, the unusual twilight coloration, and the reddish haloes seen around the Sun. Even if some doubt persists in ambiguous cases, one can often rely on glaciochemical evidence of elevated sulfate acidity in dated polar ice cores. Caution, however, is necessary in the case of older eruptions, because published ice core dates for sulfate acidity signals before A.D. 1000 are not wholly reliable and the dating error increases with age.

[12] Ancient and medieval documentary sources have been extensively surveyed by the present author for the period before A.D. 1000 and by *Schove* [1984], with the collaboration of A. Fletcher, for the period A.D. 1 to 1000. At and around the dates of the major ice core sulfate acidity peaks and the dates of all known large volcanic eruptions (necessarily Mediterranean eruptions), the present search has been conducted more thoroughly. Nevertheless, the intent has been to be complete in all periods. In the second edition of the compilation *Volcanoes of the World* [*Simkin and Siebert*, 1994], there remain so many erroneous eruption dates that the original source catalogs have been consulted instead; for the ancient period, we have used *Stothers and Rampino* [1983a] and for the medieval period, *Alfano* [1924], *Reck* [1936], and *Tanguy* [1981]. Our results now follow.

2.1. Seventeenth or Sixteenth Century B.C.

[13] Fiery red sky glares [*Hunger*, 1992; *Foster et al.*, 1996] and an eleven-month invisibility of Venus [*Reiner and Pingree*, 1975; *Baillie*, 1995] seem to have occurred at least once very early in Mesopotamian history, as did a period of dimmed sunlight in very early Chinese history

[*Pang et al.*, 1989]. Some of these undated phenomena may be associated with the Bronze Age eruption of Thera (Santorini), as *Foster et al.* [1996], *Baillie* [1995], and *Pang et al.* [1989] have speculated. For this great eruption, historical information [*Foster et al.*, 1996] favors the sixteenth century, whereas tree ring data [*Baillie*, 1999; *Manning et al.*, 2001] and ice core data [*Hammer et al.*, 1987; *Zielinski et al.*, 1994; *Clausen et al.*, 1997] suggest the seventeenth century. The undated sky phenomena are useless for fixing the date.

2.2. Sixth Century B.C.

[14] There was an "eclipse" of the Sun that lasted a whole month, according to Xenophanes (pseudo-Plutarch, *Epitome* 2.24; Stobaeus, *Eclogae* 1.25). Since Xenophanes (sixth century B.C.) displays a special scientific interest in solar eclipses [*Bicknell*, 1967], his testimony is highly credible. A prolonged dimming of the Sun's light could have been due to a volcanic aerosol veil.

2.3. 217 B.C.

[15] The Sun's disk seemed to be diminished, and the Sun appeared to be struggling with the Moon (Livy 22.1.9–10). It is very unlikely that this solar darkening in central Italy arose from an eruption of Vesuvius, as was once suggested [*Stothers and Rampino*, 1983a, 1983b]. Most of the available literary and volcanological evidence runs counter to such a proposal [*Rosi et al.*, 1987; *Forsyth*, 1990a; *Rolandi et al.*, 1998]. A partial solar eclipse on 11 February 217 B.C., however, would have been visible over central Italy [*von Oppolzer*, 1887; *Ginzel*, 1899].

2.4. 212–200 B.C.

[16] The Sun seemed to be redder than usual, like the color of blood, in 212, and appeared red throughout the day when skies were clear, in 200, as seen from parts of central Italy (Livy 25.7.8., 31.12.5). *Forsyth* [1990b] has previously pointed out the Italian report of a halo-corona complex around the Sun in 203 (Livy 30.2.12). Babylonian observers, too, reported a halo around the Sun in 203, but such reports are very common there [*Sachs and Hunger*, 1989]. For three months during the year 208, stars were invisible from northern China [*Pang et al.*, 1987]. In addition, there was a pronounced cooling at high latitudes during the years 208–204, as indicated by northern tree ring data [*Baillie and Munro*, 1988; *Baillie*, 1995]. All of these phenomena can be invoked as evidence for a recurrent or a prolonged volcanic dry fog, just as *Hammer et al.* [1980] first proposed on the basis of a strong acidity peak in the Camp Century, Greenland ice core, dated at 210 ± 30. However, other Greenland ice cores, although better dated, do not show such a peak, or at least a strong one [*Zielinski et al.*, 1994; *Clausen et al.*, 1997]. Perhaps the eruptions were only of modest size. The historical data seem to suggest that at least two eruptions occurred between 212 and 200.

2.5. 145–144 B.C.

[17] Redness occurred repeatedly in the eastern and western skies over Babylon during September–October 145 and during July–August 144 [*Sachs and Hunger*, 1996]. This is the only report of such a persistent red sky phenomenon in the nearly continuous record of well-dated astronomical and meteorological events reported at Babylon during the last four centuries B.C. [*Sachs and Hunger*, 1988, 1989, 1996]. The redness seen in 145 and 144 was most likely due to a volcanic dry fog. Although no obvious reference to it appears in Greco-Roman literature, this period is very poorly documented in Western sources. A moderate acidity peak in a Greenland ice core crops up at around 147–149 [*Zielinski et al.*, 1994; *Clausen et al.*, 1997], a date which could well be off by a few years.

2.6. 122–121 B.C.

[18] A sky bow (presumably seen at Rome) surrounded the Sun in 121 (Pliny the Elder 2.98). Mount Etna erupted in 122, and if Obsequens's (32) reported reach of the ashfallout as far as Catania can be used as valid evidence, this was possibly the largest Etnan eruption during classical antiquity before 44 B.C. [*Stothers and Rampino*, 1983a]. Concerning the sky bow, although its color is unknown, see our remark below about 90 B.C.

2.7. 90 B.C.

[19] A red ring surrounded the Sun (Pliny the Elder 2.98). This isolated report is mentioned only because the unusual halo color, red, suggests Bishop's ring, an indicator of stratospheric dry fog.

2.8. 44–42 B.C.

[20] Many manifestations of dry fog appeared both in Italy [*Stothers and Rampino*, 1983a; *Rampino et al.*, 1988] and in northern China [*Schove*, 1951; *Pang et al.*, 1986; *Pang*, 1991]. The most intense phase of the dry fog probably lasted 9–10 months during the year 44. Long assumed to be due to ordinary cloudiness [*Ginzel*, 1899; *Boll*, 1909], the darkened skies were first associated with the eruption of Mount Etna in 44 B.C. by *Hammer et al.* [1980]. The volcano connection has been pursued by many others since then [*Forsyth*, 1988; *Scuderi*, 1990a; *Bicknell*, 1993; *Baillie*, 1995; *Ramsey and Licht*, 1997]. Greenland ice cores show greatly elevated acidities in layers that have been dated between 54 and 40 B.C. [*Hammer et al.*, 1980; *Herron*, 1982; *Hammer*, 1984; *Johnsen et al.*, 1992; *Zielinski et al.*, 1994; *Zielinski*, 1995; *Clausen et al.*, 1997]. *Zielinski* [1995] found, specifically, two acidity peaks at 53 ± 2 and 43 ± 2 B.C., the older one arising from perhaps a very high-latitude eruption and the younger one from Etna. A supposed eruption of Etna in 50–49 (Lucan 1.545–548; Petronius 122.135–136) seems now to have been a literary transfer of the 44 eruption reported by Vergil (see the scholia to Lucan 1.543–547) [*Rampino et al.*, 1988; *Mynors*, 1990, p. 92].

2.9. A.D. 14

[21] The Sun as a whole was "eclipsed" (Cassius Dio 56.29.3; Eusebius, *Chronicle*, Olymp. 198; Dexter, *Chronicle*, Migne, *PL*, *31*, 66). Since there was no true eclipse of the Sun in the year 14 [*von Oppolzer*, 1887], this report might refer to a dry fog. On the other hand, Augustus Caesar died in 14, and according to Dio, the solar darkening was an omen of his death. So it could

have been just a meteorological darkening (a parallel would be the Crucifixion darkness reported in the New Testament). *Schove* [1984], however, regarded the darkening as a misdated record of the partial solar eclipse of 15 February A.D. 17.

2.10. A.D. 536–537

[22] A dry fog lasting 12–18 months covered the Mediterranean area and probably also the Middle East [*Stothers and Rampino*, 1983a; *Stothers*, 1984; *Rampino et al.*, 1988]; possibly it even reached northern China [Pang and Chou in the work by *Weisburd*, 1985]. The climatic and social repercussions of this event have formed the subject of four recent books [*Baillie*, 1999; *Keys*, 1999; *Gill*, 2000; *Gunn*, 2000] as well as many research papers. The source volcano is unknown, although Rabaul, Papua New Guinea [*Stothers*, 1984], some unidentified high-latitude volcano [*Stothers*, 1999], Krakatau, Indonesia [*Keys*, 1999], and El Chichón, Mexico [*Gill*, 2000] have all been suggested. Dates of elevated acidity in Greenland ice cores scatter between 516 and 540 [*Hammer et al.*, 1980; *Herron*, 1982; *Hammer*, 1984; *Zielinski*, 1995; *Clausen et al.*, 1997]. Although a meteoritic source of the dry fog has been proposed [*Clube and Napier*, 1991; *Baillie*, 1994], the volcano hypothesis seems to be more plausible on both glaciochemical and historical grounds [*Stothers*, 1999].

2.11. A.D. 626–627

[23] The Sun was dimmed for 8–9 months over the eastern Mediterranean and, apparently, over Ireland [*Stothers and Rampino*, 1983a]. This was doubtless due to a volcanic dry fog. The year is somewhat uncertain. Syriac chroniclers writing in the early eighth century give 627 as the date of two (nonexistent) "eclipses" of the Sun and Moon (James of Edessa, *Chronicle*, p. 250, Brooks; *Chronicle to A.D. 724*, p. 113, Chabot), while Syriac writers of the tenth to thirteenth centuries provide the year 626 together with a more detailed description of the solar darkening (Agapius, *Universal History*, p. 452, Vasiliev; Michael the Syrian, *Chronicle* 11.409, Chabot; Bar-Hebraeus, *Chronography* 10.96, Budge; *Chronicle to A.D. 1234*, p. 181, Chabot). Various Irish chroniclers mention a darkness in 624, a year that becomes 625 after applying a needed chronological correction [*Schove*, 1984]. A date of 625 would harmonize with a reliable Japanese climatic report that unusually cold and rainy weather broke out in Japan during the summer of 626 (two years before the reported total solar eclipse of 10 April 628) (*Nihongi* 22.39–40, Aston). This accounting of the available evidence would clear up the confused discussions of *Newton* [1972] and *Schove* [1984], which implied several solar darknesses occurring in the period 617–629. Greenland ice cores show elevated levels of acidity at years placed variously in the range 622–640 [*Hammer et al.*, 1980; *Hammer*, 1984; *Zielinski et al.*, 1994; *Zielinski*, 1995; *Clausen et al.*, 1997].

2.12. A.D. 744

[24] The Sun became dim and blood-colored, the atmosphere misty and dark, for five or six days in August (Theophanes Confessor, *Chronography*, Migne, *PG*, *108*, 849; Anastasius, *History*, Migne, *PG*, *108*, 1373; Agapius, *Universal History*, p. 520, Vasiliev; George Cedrenus, *Histories*, Migne, *PG*, *121*, 885; *Historia Miscella*, Muratori, *RIS*, *1*(1), 156). This event was reported from the Middle East, and the year is now quite securely established [*Mango and Scott*, 1997]. In the same year, northwestern Germany experienced a strange fall of ash (*Annals of Xanten, MGHSS*, *2*, 221), which ought not to be confused with a Middle Eastern dust storm that occurred in the spring of 742. If the ashfall and the dim Sun are associated, they suggest a volcanic eruption in Iceland with strong northwesterly winds blowing. Greenland ice cores show an acidity signal in 743 or 744, but this signal is fairly weak, perhaps owing to the unfavorable wind direction [*Hammer et al.*, 1980; *Clausen et al.*, 1997].

2.13. A.D. 797–798

[25] The Sun was darkened for 17 days in A.D. 797 and did not cast its rays, with the result that ships at sea went off course (Theophanes Confessor, *Chronography*, Migne, *PG*, *108*, 952; George the Monk, *Chronology*, Migne, *PG*, *110*, 968; Anastasius, *History*, Migne, *PG*, *108*, 1405–1406; George Cedrenus, *Histories*, Migne, *PG*, *121*, 909; Leo Grammaticus, *Chronography*, Bonn, *CSBH*, *47*, 199; *Historia Miscella*, Muratori, *RIS*, *1* (1), 170; Michael Glycas, *Annals*, Migne, *PG*, *158*, 532). Theophanes was probably the original source for all the later Byzantine and Italian chroniclers. French chroniclers, some of them contemporary with Theophanes, and also later German chroniclers, have recorded that the sidus Martis (the southern constellation Scorpius [*Allen*, 1963]) could not be seen from July 797 to the following July (*Annales Tiliani*, Bouquet, *5*, 23, *Annales Loiseliani*, Bouquet, *5*, 320; *Annals of Lorsch*, *MGHSS*, *1*, 184; Ado of Vienne, *Chronicle*, Bouquet, *5*, 320; Regino of Prüm, *Chronicle, MGHSS*, *1*, 562). Since at the latitudes of France the first-magnitude star α Scorpii culminates low near the horizon on 11 July, a total zenithal optical depth of $\sim$1 would suffice to produce the minimally needed 4 magnitudes of extinction. From Theophanes's account of solar darkening, *Newton* [1972] and *Schove* [1984] have inferred a volcanic aerosol veil. This is supported by the Crête, Greenland, ice core (although not by any others), in which the largest acidity peak between the years 626 and 934 falls in the year 798 ± 2 [*Hammer et al.*, 1980]. Therefore, this eruption may have been important enough to cause climatic cooling. The *Annals of Ulster* (A.D. 798) mentions a "great snow" in 798, while northern tree ring data indicate very cool summers in the period 794–800 [*Briffa et al.*, 1990; *Scuderi*, 1990b, 1993]. Observation and mention of the odd fact about stellar extinction doubtless reflects France's reawakened interest in astronomy during the brief period of the Carolingian Renaissance. The very large extinction over Europe suggests a local (perhaps Icelandic) eruption.

2.14. A.D. 897

[26] Red skies in Egypt made the outdoor surroundings appear red (Eutychius of Alexandria, *Annals*, Migne, *PG*, *111*, 1144; al-Tabari, *Annals*, A.H. 284; Elias of Nisibis, *Chronicle*, p. 92, Brooks). This event, which occurred only on 5 May and only near Alexandria, was apparently

caused by a red sandstorm, as mentioned by the chroniclers. It is extremely unlikely to be related to the moderate acidity peak seen in Greenland ice cores somewhere in the years 898–903 [*Hammer et al.*, 1980; *Zielinski et al.*, 1994; *Zielinski*, 1995; *Clausen et al.*, 1997]. Similarly, a violent storm accompanying an earthquake in Egypt seems to have created a red Sun on 13 May 963 (al-Antaki, quoted by *Guidoboni* [1994, p. 398]). Redness of the northeastern sky at some time in 977 or 978 (Ibn al-Athir, quoted by *Guidoboni* [1994, p. 401]) may have been due to another sandstorm or else to an auroral display.

2.15. A.D. 934

[27] A dry fog is strongly indicated by a day-long red appearance of the Sun over Germany and Ireland [*Stothers*, 1998]. *Schove* [1984] has noted four other mentions of the red Sun in very late European chronicles, all of which have referred the event to the reign of Lothair II (931–950) in Italy. The assigned dates in these chronicles range from 937 to 963, but these are undoubtedly errors for 934, the date implied, somewhat approximately, by our main source, the contemporary chronicler Widukind of Corvey in Saxony. The volcano Eldgjá in Iceland erupted around this time, probably starting during the summer months. Greenland ice cores place the eruption date somewhere in the interval 934–938 [*Hammer et al.*, 1980; *Herron*, 1982; *Hammer*, 1984; *Johnsen et al.*, 1992; *Zielinski et al.*, 1994, 1995; *Zielinski*, 1995; *Clausen et al.*, 1997]. Although northern tree ring signals around this date are sparse [*D'Arrigo et al.*, 2001], the documentary evidence is abundant and quite explicit about the atmospheric cooling (see also the contemporary Persian chronicler Hamza al-Isfahani, *Annals* 10.7, Gottwaldt). Climatic and historic evidence together tie the starting date to 934. The eruption itself was of fissure type and was apparently drawn out over several years [*Thordarson et al.*, 2001].

3. Lunar Eclipse Observations

[28] During a total or partial eclipse of the Moon, the Sun's rays are refracted, and to a lesser extent scattered, into the shadow cone by particles in the Earth's upper atmosphere. The bending of the Sun's light bathes the lunar surface with mostly longer wavelengths, endowing it with a reddish or coppery color. If the upper troposphere is filled with clouds or if the stratosphere contains widespread volcanic aerosols, the Moon will appear dark or even disappear entirely. Partial cloudiness, however, will cause the Moon to exhibit a variety, and even a progression, of different colors [*Olivier*, 1966]. From time immemorial, the reddened face of the eclipsed Moon must have been obvious to the casual observer (e.g., Ovid, *Amores* 1.8), but the correct physical explanation of the redness and of the other colors persistently eluded the ancient and medieval experts in all cultures, including Mesopotamia [*Rochberg-Halton*, 1988], the Greco-Roman world (Plutarch, *On the Face in the Moon* 934; Ptolemy, *Tetrabiblos* 2.9; Hephaestion of Thebes 1.21.2), and the Arabic world (al-Biruni, *Coordinates* 168–169, Ali). Kepler in 1617 was the first author to give the correct explanation of the reddening, and Flammarion in 1884 explained the darkening after volcanic eruptions.

[29] Several catalogs of lunar eclipse reports in ancient and medieval literature have been prepared during the past five centuries. We have used here the four most recent catalogs; *Ginzel* [1899] and *Boll* [1909] for 900 B.C. to A.D. 600, *Newton* [1970, 1972] for 900 B.C. to A.D. 1000, and *Schove* [1984] for A.D. 1 to 1000. In all cases, the original literature has been freshly consulted in order to evaluate the accuracy and context of all the reports. Identifications of particular eclipses have been accepted from either Boll or Schove with only minor exceptions. We cite months and days from *von Oppolzer*'s [1887] catalog of calculated eclipses. Lunar eclipses are not rare in nature, and observable total lunar eclipses occur about once a year on the average [*Keen*, 1983], but they are not often reported in the early literature.

[30] It is insufficient to know that an eclipse has been reported in order to use that eclipse. One must also determine whether it was an observed eclipse or merely a calculated eclipse. If a color was reported, was it an actual observation or just a stock color description? In view of the fact that an eclipse color is rarely mentioned by any early chronicler and, if one is, the chronicler in most cases was a contemporary of the event, we can usually regard the color as an actual observation rather than a mere synonym for the word "eclipsed", unless there is evidence to the contrary. If no color at all is mentioned as is usually the case, we shall ignore the eclipse, even though one might be tempted to assume that this was a normal, reddish eclipse. Probably in nearly all cases it was, but our purpose is to present actual known data about the color, which can then reveal with some certainty the state of stratospheric transparency.

3.1. Dark Lunar Eclipses

3.1.1. 21 June 168 B.C.

[31] The moon grew black, lost its light, turned all sorts of colors, and then disappeared (Plutarch, *Aemilius Paulus* 17.7–8). No other ancient author who mentions this eclipse, including the contemporary Polybius, provides these details (Polybius 29.16; Cicero, *On the Republic* 1.23; Livy 44.37; Justin-Trogus 33.1; Valerius Maximus 8.11.1; Pliny the Elder 2.53; Quintilian 1.10.47; Frontinus, *Stratagems* 1.12.8; Cassius Dio in Zonaras 9.23; Julius Paris 8.11.1). Plutarch's (circa A.D. 100) account, however, does accurately describe a total lunar eclipse. The umbra appears quite black (by contrast) when it first encroaches on the Moon [*Russell et al.*, 1945]. As the moonlight begins to fade, a succession of lunar colors make their appearance if the Earth's limb is partly clouded, causing sunlight to be refracted from different layers of the atmosphere [*Olivier*, 1966]. Plutarch's report of the Moon's subsequent disappearance suggests that rotation of the Earth eventually brought a more extensively clouded area to the limb. Alternatively, rising clouds might have blocked the viewer's line of sight, as happened at the total lunar eclipse of 27 September A.D. 14 (Tacitus, *Annals* 1.28; Cassius Dio 57.4.4). Whether Plutarch's report of the Moon's final disappearance implies a truly dark eclipse is, therefore, at best questionable [*Bicknell*, 1968, 1983; *Stothers*, 1986]. Although it is possible that Plutarch is simply quoting

astrological tradition concerning the expected colors of lunar eclipses [*Fotheringham*, 1921; *Stothers*, 1986], he may well have gotten an actual account from a book by the astronomer Sulpicius Gallus, who witnessed the eclipse and then wrote a book about eclipses (Pliny the Elder 1.2, 2.53). The issue remains undecided.

3.1.2. 63–44 B.C.

[32] The eclipsed Moon appeared to vanish on several occasions (Lucretius 5.751; Cicero, *On Divination* 1.18, 2.17). *Bicknell* [1983, 1987] has argued that both Lucretius and Cicero witnessed and described a number of dark total lunar eclipses during their lifetimes. He also has speculated that the sorceress Aglaonice, who reputedly could "draw down" the Moon, lived around this time and took clever advantage of those eclipses. Opposed to these views are arguments that Lucretius and Cicero in their poems were only indulging in stock descriptions and poetic phrases, and that Aglaonice, if not purely mythological, lived before the fifth century B.C. [*Stothers*, 1986, 1987]. There is no independent scientific evidence one way or the other in this case, but a long string of dark lunar eclipses is not attested in any other historical period.

3.1.3. 19 November A.D. 560

[33] The Moon was darkened and could hardly be seen (Marius of Avenches, *Chronicle, MGHAA*, *11*, 237). The chronicler Marius, a contemporary, probably witnessed this eclipse himself.

3.1.4. 31 December A.D. 567

[34] The Moon was not visible (*Excerpta Sangallensia, MGHAA*, *9*, 335). The St. Gall extracts were put together in the seventh century, but are reliable for events in the previous century [*Schove*, 1984].

3.1.5. 11 December A.D. 577

[35] The Moon frequently turned black in this year (Gregory of Tours, *History of the Franks*, Bouquet, *2*, 249). The partial eclipse of 11 December was the only lunar eclipse that occurred in 577 [*von Oppolzer*, 1887]. Although Gregory of Tours was a contemporary author, any physical significance of his term "black" can be strongly doubted in view of the similar language he used for the eclipse of 5 April 581, which likewise was only partial. More generally, Gregory always wrote on astronomical matters in exaggerated, and even naively miraculous, terms (*On Stars' Courses, MGHSRM*, *1*(2), 410, 413).

3.1.6. 5 April A.D. 581

[36] The Moon grew very dark (Gregory of Tours, *History of the Franks*, Bouquet, *2*, 257). Being partial, this was probably not a truly dark eclipse (see our remarks above about the eclipse of 11 December 577).

3.1.7. 4 January A.D. 763

[37] The moon appeared dark (*Annals of Ulster*, A.D. 761; Tigernach, *Annals*, p. 260, Stokes). Since the Moon during the eclipse of 13 December 726 was described by the *Annals of Ulster* (under A.D. 724) as being both dark and blood-colored, the mention here of only darkness is probably significant. Because early medieval dates listed in the Irish chronicles can often be in error by up to 4 years, there is no need to doubt the identification of this eclipse as given by *Schove* [1984]. The *Annals of Ulster* is composed of successive additions of text onto a core that was put together at an early date, and therefore it presents reliable (except for dates) contemporary information from about the middle of the sixth century. Since the color of a lunar eclipse is not always noted, a color when stated can be assumed to be a genuine observation.

3.1.8. 4 December A.D. 773

[38] The Moon appeared dark (*Annals of Ulster*, A.D. 772). This is probably a genuine observation (see our remarks above about the eclipse of 4 January 763).

3.1.9. 30 March A.D. 861

[39] The Moon turned black (*Annals of St. Bertin, MGHSS*, *1*, 454). Since the *Annals of St. Bertin* also records the eclipses of 18 April 832 and 5 December 838, but does not mention their color, the blackness described here is probably significant.

3.2. Reddish Lunar Eclipses

3.2.1. 27 August 413 B.C.

[40] The Moon lost its light and emitted all sorts of colors (Plutarch, *Nicias* 23.1–2). Since these color details are not mentioned by Thucydides (7.50), who was a contemporary, or by any other late author (Polybius 9.19; Diodorus Siculus 13.12.6; Pliny the Elder 2.54; Quintilian 1.10.47), Plutarch probably supplied them as a literary gloss. The context in which he mentions them has, in fact, a distinctly didactic tone, and he fails to mention them in an independent account of the same eclipse (*On Superstition* 169A). We have already had occasion to doubt the similar details given by him for the eclipse of 21 June 168 B.C.

3.2.2. 20 September 331 B.C.

[41] The Moon faded at first and then appeared blood-colored (Quintus Curtius 4.10.2). Almost certainly, Curtius (a rhetor writing in the first century A.D.) is inventing the color remark as no other author, not even Plutarch, records a color for this eclipse (Cicero, *On Divination* 1.121; Pliny the Elder 2.180; Plutarch, *Alexander* 31.4; Ptolemy, *Geography* 1.4; pseudo-Callisthenes 3.17; Julius Valerius 3.27; scholium to Aratus, p. 317, Maass). *Bicknell* [1983], however, accepts the color remark as a genuine observation, taken from Curtius's unknown source.

3.2.3. 17 March 284 B.C.

[42] The eclipse of the Moon was red [*Steele*, 2000, p. 42]. This was a total lunar eclipse [*von Oppolzer*, 1887].

3.2.4. 1 August 226 B.C.

[43] The eclipse of the Moon was red [*Sachs and Hunger*, 1989]. This was a total lunar eclipse [*von Oppolzer*, 1887].

3.2.5. 4 October 183 B.C.

[44] The eclipse of the Moon was red [*Sachs and Hunger*, 1989]. This was a partial lunar eclipse [*von Oppolzer*, 1887].

3.2.6. 21 March 135 B.C.

[45] The eclipse of the Moon was red [*Sachs and Hunger*, 1996]. This was a total lunar eclipse [*von Oppolzer*, 1887].

3.2.7. 1 June 120 B.C.

[46] The eclipse of the Moon was reddish [*Sachs and Hunger*, 1996]. This was a total lunar eclipse [*von Oppolzer*, 1887].

3.2.8. 1 May 109 B.C.

[47] The eclipse of the Moon was red-brown [*Sachs and Hunger*, 1996]. This was a partial lunar eclipse [*von Oppolzer*, 1887].

3.2.9. 25 August 106 B.C.

[48] The eclipse of the Moon was red [*Sachs and Hunger*, 1996]. This was a total lunar eclipse [*von Oppolzer*, 1887].

3.2.10. 3 April A.D. 33

[49] The Moon turned blood-colored and failed in its light (pseudo-Pilate, *Report of Pilate*). *Humphreys and Waddington* [1983] have tried to use this undated New Testament Apocryphal fragment, together with the apostle Peter's (Acts 2:20) mention of a prophecy by Joel (2:31) about the Moon's turning to blood, in order to bolster their case for a report of an actual lunar eclipse at the time of the Crucifixion. However, the *Report of Pilate* is almost universally regarded as a late Christian forgery, put together from standard New Testament material. The only possibly relevant lunar eclipse in the years around the uncertain time of the Crucifixion is 3 April 33. Since this partial eclipse was visible only at moonrise and had a negligible magnitude [*Schaefer*, 1990], the eclipse in the *Report of Pilate* can be regarded as fictitious.

3.2.11. 18 October A.D. 69

[50] The Moon appeared both blood-colored and black, and emitted still other terrifying colors (Cassius Dio 64.11). *Ginzel* [1899] and *Boll* [1909] have questioned Dio's account on the grounds that this eclipse was only a partial one [*von Oppolzer*, 1887]. In fact, Dio's description of it sounds purely literary and was perhaps taken from Plutarch's lost *Life of Vitellius*. Tacitus, a contemporary, does not mention the eclipse at all.

3.2.12. 31 August A.D. 304

[51] The Moon turned blood-colored (*Martyrdom of Felix*, 24 October, Bollandists). The date of the martyrdom, the identity of Felix, and the eclipse itself are all so highly questionable [*Schove*, 1984] that we may safely dismiss this report as pure hagiography (compare 3 April A.D. 33).

3.2.13. 2 March A.D. 462

[52] The Moon turned blood-colored (Hydatius, *Chronicle, MGHAA*, *11*, 32; Fredegar, *Chronicle, MGHSRM*, *2*, 77). This report seems to be based on an authentic observation, in view of the fact that Hydatius, a contemporary chronicler, mentions the lunar eclipse of 26 September 451 without giving a color.

3.2.14. 10 November A.D. 672

[53] The Moon turned blood-colored (*Annals of Clonmacnoise*, A.D. 670; *Annals of Ulster*, A.D. 673; *Chronicum Scotorum*, A.D. 670; Tigernach, *Annals*, p. 203, Stokes). This color detail, like others in the Irish chronicles, can be regarded as genuine.

3.2.15. 16 April A.D. 683

[54] The face of the Moon was blood-colored (Anastasius, *Lives of the Popes*, Migne, *PL*, *128*, 849–850). Although Anastasius (the Vatican librarian) was a ninth-century author, his report is probably reliable since he does not give such a color detail for the lunar eclipse of 17 June 680.

3.2.16. 11 November A.D. 691

[55] The moon turned blood-colored (*Annals of Clonmacnoise*, A.D. 687; *Annals of Ulster*, A.D. 691; *Chronicum Scotorum*, A.D. 688; Tigernach, *Annals*, p. 212, Stokes). Several Welsh and Danish chronicles apparently refer to the same eclipse, possibly relying on the Irish accounts [*Schove*, 1984]. The eclipse was only a partial one [*von Oppolzer*, 1887].

3.2.17. 13 January A.D. 716

[56] The Moon appeared blood-red (Anastasius, *Lives of the Popes*, Migne, *PL*, *128*, 975–976). Note that Anastasius mentions the Moon's color for this eclipse as well as for the eclipse of 16 April 683, but not for that of 17 June 680. The color remark is believable.

3.2.18. 13 December A.D. 726

[57] The Moon was dark and blood-colored (*Annals of Ulster*, A.D. 724).

3.2.19. 24 January A.D. 734

[58] The Moon was blood-colored and then black (Continuator of Bede, *Chronicle*, Migne, *PL*, *95*, 290). The word "black" probably refers to the edge of the umbra during the time of egress.

3.2.20. 24 January A.D. 753

[59] The Moon was blood-colored (*Annals of Clonmacnoise*, A.D. 749; Tigernach, *Annals*, p. 254, Stokes). The continuator of Bede (*Chronicle*, Migne, *PL*, *95*, 292) says that the Moon was eclipsed by "a very black shield". Although this eclipse was only partial [*von Oppolzer*, 1887], the umbra would undoubtedly appear dark by contrast with the brighter parts of the Moon's disk.

3.2.21. 23 November A.D. 755

[60] The Moon appeared blood-red (Simeon of Durham, *History of the Kings*, A.D. 755). The color remark seems to be authentic, in view of the absence of such a detail given in Simeon's notices of the eclipses of 31 July 752 and 28 March 796. Although Simeon wrote in the twelfth century, his sources were reliable for this period (see our remarks above about the eclipse of 4 January 763).

3.2.22. 26 February A.D. 788

[61] The Moon was blood-red (*Annals of Ulster*, A.D. 787).

3.2.23. 26 February A.D. 807

[62] The Moon turned blood-colored (*Annals of Ulster*, A.D. 806; *Chronicum Scotorum*, A.D. 807).

3.2.24. 1 April A.D. 926

[63] The Moon paled and then turned blood-colored (Flodoard of Reims, *Annals, MGHSS*, *3*, 376). This report and all those that follow were made by continental European chroniclers who most likely were eyewitnesses.

3.2.25. 4 September A.D. 936

[64] The Moon appeared blood-colored and illuminated the night very little (Flodoard of Reims, *Annals, MGHSS*, *3*, 383). The faintness of this eclipse is probably attributable to lingering stratospheric aerosols after the massive Eldgjá eruption of 934.

3.2.26. 4 September A.D. 955

[65] The Moon turned blood-colored (Fleury chronicler, *History of the Franks*, Bouquet, *8*, 299; *Annals of Fleury*, Bouquet, *8*, 254).

3.2.27. 15 August A.D. 965

[66] The Moon turned blood-colored (*Annals of Prüm, MGHSS*, *15(2)*, 1292).

3.2.28. 14 July A.D. 995

[67] The Moon turned blood-colored (*Annals of Augsburg, MGHSS*, *3*, 124).

3.2.29. 6 November A.D. 998

[68] The Moon turned blood-colored (*Annals of Regensburg, MGHSS*, *17*, 584; *30*(2), 746).

4. Discussion

[69] The present study of primary written sources for the historical period before A.D. 1000 has turned up a number

of lesser stratospheric dry fogs in addition to the four prominent ones already known. To 44 B.C. and A.D. 536, 626, and 934, we can now add, with some confidence: 212–200 and 145 B.C. and A.D. 744 and 797; also, with rather less confidence, an unidentified year in the sixth century B.C. and, perhaps, 121 and 90 B.C. Mount Etna in Sicily gave birth to the two dry fogs of 121 and 44 B.C., while Iceland's Eldgjá produced the A.D. 934 northern haze. All of these dry fogs have been detected from either direct or indirect observations of the Sun. To these dry fogs can be added five other good cases, inferred from the reported darkness of total lunar eclipses in A.D. 560, 567, 763, 773, and 861. Although it is not certain whether stratospheric aerosols or cloudy tropospheric meteorological conditions were responsible for the eclipse darkness, modern experience suggests that stratospheric aerosols nearly always dominate the picture [*Keen*, 1983, 2001].

[70] Within the interval 300 B.C. to A.D. 1000, the presently detected dry fogs are distributed more or less randomly, giving us some confidence about the near completeness of our sample for intense dry fogs. This belief is supported by the evidence of measured high acidities in Greenland ice cores at or near the corresponding dry fog dates. In contrast, the distribution of total lunar eclipses with reliably reported colors is greatly skewed toward the period after A.D. 400. This asymmetry arises in large measure from the paucity of ancient Greco-Roman eclipse reports, since eclipses in that culture tended to be mentioned only in association with important historical events and then were embellished with rhetorical textbook descriptions [*Fotheringham*, 1921]. A unique exception is the cluster of notices about reddened lunar disks in 284, 226, 183, 135, 120, 109, and 106 B.C. reported from Babylon. It is clear that these seven eclipses do not support *Bicknell*'s [1983] conjecture, based on insufficient Greco-Roman sources, that dark total lunar eclipses might have been common between 168 and 44 B.C.

[71] Assuming that lunar eclipse colors have been randomly chronicled during the period A.D. 400–1000, we may estimate the ratio R of dark to normal lunar eclipses from our presently compiled numbers of such eclipses. We thus obtain R = 5/15 = 0.33. To compare this result with modern total lunar eclipses, we use *Keen*'s [1983, 2001] tabulation of 38 eclipses observed during the years 1960–2001, for which he has derived stratospheric visual optical depths, τ_{vis}. For the preceding years 1881–1959, we use *von Oppolzer*'s [1887] list of total lunar eclipses, together with our pyrheliometrically derived values of τ_{vis} [*Stothers*, 1996]. Over the whole interval 1881–2001, the smallest value of τ_{vis} for which naked-eye observers of the Moon have called the eclipse "dark" is 0.04 ± 0.02, based on the three eclipses of 16 October 1902 [*Link*, 1963], 15 September 1913 [*Link*, 1963], and 18 December 1964 [*Anonymous*, 1964, 1965]. Adopting, therefore, $\tau_{vis} = 0.04$ as the dividing value between "dark" and "normal" eclipses, we find from *Keen*'s [2001] homogenous eclipse data the result R = 9/29 = 0.31. We thus conclude that the frequency and intensity of volcanic eruptions throughout the world during the early Middle Ages were close to what we have experienced in the course of the last 40 years. Although fluctuations in volcanic activity certainly took place over the past 16 centuries [e.g., *Stothers*, 1989, 1996], these seem to have operated on subcentury timescales.

[72] An optical depth of 0.04 implies a total aerosol mass of $\sim$6 Tg contained in the global aerosol veil [*Stothers*, 1996]. By comparison, a glaciochemical analysis of ice cores is able to detect from background noise only an aerosol veil with a mass of $\sim$30 Tg or greater [*Clausen et al.*, 1997]. Thus a Pinatubo-sized eruption would be barely detectable in polar ice cores. Although the advantage of the lunar eclipse method for dry fog detection is obvious, the downside of the method is that early historical reporting of lunar eclipses is very sporadic and is never detailed enough to yield anything but a lower limit on the aerosol mass.

[73] How well do our direct Mediterranean detections of the larger aerosol veils agree with detections of sulfate aerosols using ice cores from Greenland? *Hammer et al.* [1980] have analyzed the Crête ice core (which starts at A.D. 553) and have found six large acidity peaks before A.D. 1000; these occur at A.D. 623, 757, 798, 841, 934, and 971. Allowing for some dating uncertainty, three of these peaks correlate with historical dry fogs at 626, 797, and 934, while a slightly smaller acidity peak at 744 agrees with another historical dry fog of the same date. Thus, the historical method picks up about half of the largest events in the Crête ice core. From the work of *Clausen et al.* [1997], who have intercompared the Crête, Dye 3, and GRIP ice cores, it would seem that the smallest of the six large Crête acidity peaks lies near the threshold of distinguishability from background noise. The detailed comparisons of Dye 3 and GRIP ice cores have yielded nine significant sulfate peaks in the interval from 600 B.C. to A.D. 1000, namely at 244, 147, and 49 B.C., and at A.D. 516, 572, 757, 871, 898, and 934. Since four historical events at 145 and 44 B.C. and at A.D. 536 and 934 agree with dates from Clausen et al. within the possible errors, the historical method has again picked up about half of the largest ice core events. Last, *Zielinski et al.* [1994] have detected 29 sulfate peaks lying between 100 B.C. and A.D. 1000 in the GISP2 ice core. In view of the results of Clausen et al., it is unclear how many of these GISP2 sulfate peaks are truly significant, but the four largest occur at 53 B.C. and at A.D. 78, 640, and 939 [*Zielinski et al.*, 1994; *Zielinski*, 1995], with some uncertainty in the dating. The dry fog events at 44 B.C. and at A.D. 626 and 934, as well as the famous eruption of Vesuvius in A.D. 79, suggest that the strongest GISP2 signals can possibly all be accounted for by the historical data.

[74] It remains undetermined how many of the lesser of these Greenland signals are only noise spikes. This problem and the equally serious problem of accuracy in ice core dating have been discussed in detail by *Robock and Free* [1995], without any resolution at present. Another problem is the exaggerated signal produced by local volcanoes. This bias affects both the ice core method (Icelandic and Alaskan volcanoes) and the historical method (Mediterranean and Icelandic volcanoes). Local wind transports, however, can moderate or exacerbate the bias. Although the historical method is not as prone to contamination by false events, it is not wholly immune to them. All in all, present evidence suggests that the thresholds for detectability of large volcanic eruptions during the period under consideration

Table 1. Phenomena Indicating the State of Stratospheric Transparency, 600 B.C. to A.D. 1000

Sun-Related Phenomena	Dark Total Lunar Eclipse	Reddish Lunar Eclipse	Reddish Lunar Eclipse
Sixth century B.C.	(168) B.C.	(413) B.C.	A.D. 691
(217)	(63–44)	(331)	716
212–200	A.D. 560	284	726
145–144	567	226	734
122–121	(577)	183	753
(90)	(581)	135	755
44–42	763	120	788
A.D. (14)	773	109	807
536–537	861	106	926
626–627		A.D. (33)	936
744		(69)	955
797–798		(304)	965
(897)		462	995
934		672	998
		683	

Dates inside parentheses indicate doubtful cases.

(especially since 300 B.C.) are roughly comparable for the ice core and historical methods. An exception exists if the eruption is directly observed and reported, or if the color of a contemporary lunar eclipse is observed and reported.

[75] Table 1 summarizes all of our observational data for the years from 600 B.C. to A.D. 1000 in which information on stratospheric transparency is available. Dates enclosed in parentheses indicate questionable entries, some of them almost certainly spurious cases. These uncertain entries are very few in number, however, especially after A.D. 400. An obvious conclusion is that it is possible to infer something definite and useful about stratospheric aerosol conditions in even the earliest years of the preinstrumental historical period.

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